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Tide Gauge Disturbances from the Great Eruption of Krakatoa

by

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Abstract

The aerial disturbance from Krakatoa was recorded at many stations on at least three passages around the earth. A tidal wave on the ocean was recorded at tidal stations in almost all parts of the world. Only at nearby stations did the arrival times uniformly agree with that expected for gravity waves in the ocean; many distant arrivals were attributed to coincidental local earthquakes.

It is shown that the tidal disturbances at distant stations correlate in time with the first aerial wave arriving at the station in the direction from ocean to continent, a result which would be expected from coupling between the barometric disturbance and the ocean surface wave.

These observations have led to theoretical and experimental investigations of several types of air-coupled surface waves.

Introduction

Starting in 1949 several investigations at Lamont Geological Observatory have endeavored to explain the periods and durations of tsunami waves as the result of dispersive propagation of a gravity wave in the sea water, assuming that the initial form of the wave was a simple impulse of relatively brief duration. The periods and wave length involved are of the order of 20 minutes and 100 miles respectively. It soon appeared that yielding of ocean bottom could not produce sufficient dispersion to account for the observed duration of several hours, and attention was next turned toward possible effects of the atmosphere. Strong influence of the atmosphere seemed unlikely, due to the great density contrast and the considerable difference between velocities of the appropriate free waves in the two media, i. e. about 600 km per hour for long gravity waves in the ocean and about 1100 km/hr for long atmosphere waves like those generated in the Krakatoa explosion.

Speculation about the influence of the atmosphere in ocean gravity waves led to consideration of the inverse effect, that is, the effect of the ocean upon transmission of atmospheric oscillations of the Krakatoa type. The Report of the Krakatoa

Committee of the Royal Society (Symons, 1888) was studied.

Krakatoa, a small volcano in Sunda Strait, is famous for its eruption in 1883 which was accompanied by one of the greatest explosions ever recorded. A remarkable feature of the explosion was the barometric disturbance which travelled outward from the volcano and was recorded at many stations on at least three passages around the earth. A disastrous tsunami was initiated and oscillations were recorded by tide gauges as far away as San Francisco, Colon, and several English Channel ports.

The conclusions on propagation of the tidal disturbance which had been reached by Captain Wharton in the Royal Society Committee report may be summarized as follows: (a) To the north and east in the Java Sea the waves could be traced for 450 miles at which point they were reduced to small amplitudes. (b) To the south and east the propagation was limited, not extending beyond the west coast of Australia. (c) To the west the waves travelled over great distances, reaching Cape Horn and possibly the English Channel, the Cape Horn paths being very improbable because the velocity required great water depth in unsurveyed Antarctic waters. (d) The disturbances in the Pacific and in the Caribbean had no connection with Krakatoa, but were the results of other seismic actions, and were apparently due to more than one center of movement.

The published tide gauge records for the Krakatoa disturbance were then examined to see if any part of the tide gauge indication could be correlated with the arrival time of the air wave. It was immediately noted that, for the stations beyond the Indian Ocean which Captain Wharton could not correlate with the Krakatoa explosion on the assumption of propagation as a gravity sea wave, the arrival time of the major tidal disturbance could be correlated with the arrival of the first or second air wave. This was interpreted to mean that the energy in the tidal disturbance was being transferred to the water from the barometric disturbance when this disturbance approached the station from the ocean side. Thus coupling between the atmosphere and the ocean was recognized as a significant factor in the propagation of long period waves in either medium.

Subsequent experimental and theoretical investigations indeed verified that coupling of surface waves to the atmosphere was an important factor in Rayleigh waves from earthquakes or explosions (Haskell 1952, Press and Ewing 1951a, Benioff, Ewing and Press 1951, Jardetzky and Press 1952) and in flexural waves in floating ice sheets (Press and Ewing 1951b, Press, Crary, Oliver and Katz 1951). In general, the greater the density contrast between the two media, the greater the need for equality of

velocities in them, leading to a concept of resonant coupling at a period where the phase velocities in the two media (taken separately) are equal.

It is of interest to note that the question of tsunami duration, which initiated this series of studies, remains unsolved. In fact, efforts to explain the duration by continued action at the source rather than by dispersive propagation now seem very promising.

Studies are also being made to determine whether atmosphere-ocean coupling can account for the general similarity in periods of the background noise registered on tide gauges and on coastal barographs.

Presentation of the Data

Reference to the chart, Plate XXXV of Captain Wharton's report (Symons 1888) shows that the Indian Ocean stations (and possibly Port Moltke, South Georgia) are the only ones to which a tidal disturbance of the conventional kind can travel without demanding improbable refraction or diffraction around barriers. For example, the paths to Hawaii, Kodiak, and San Francisco must be deflected almost 180^{o} in passing around Australia. Likewise the paths to Colon and to the English Channel ports must swing sharply to round the Cape of Good Hope, and even after that must cross severe barriers. The difficulty of transmitting energy over these paths as well as the impossible velocities to which they led justified Captain Wharton's doubt that the observed energy was propagated as water waves along these paths. Until the present alternative mode of transmission of energy to these stations was suggested there seemed no alternative but to follow Captain Wharton's conclusion that unrelated seismic disturbances were responsible for the tidal waves.

It is of interest to note that although Verbeek (1886) noticed the simultaneous arrival of the aerial wave and the tidal disturbance at Colon he passed this off as a coincidence and ascribed the tidal wave to a near earthquake.

For those Indian Ocean stations for which the observations are good, reasonable paths are available for ordinary tidal waves and the travel times are not in serious disagreement with those expected from this mode of propagation. These stations will not be discussed further except for the remark that in these cases the energy brought by the ordinary tidal wave greatly exceeds that induced from the barometric wave.

The paths and travel times of the first and second passages of the barometric disturbance are shown in Figures 1 and 2, taken from Lt. Gen. Strachey's article in the Report of the Royal Society (Symons 1888). The tidal stations outside the Indian Ocean discussed by Captain Wharton are listed in Table I. Included in the table are the local times of arrival of the air wave as deduced from Figures 1 and 2, the expected time of arrival of the air induced tidal wave computed by adding Wharton's allowance for propagation in shallow water near the station, Wharton's and our arrival times for the tidal disturbance as read from the published marograms.

Wharton's readings from the marograms differ from ours for the stations at Colon, Portland, Williamstown, Honolulu, St. Paul and San Francisco. On the Colon marogram (Figure 3) we picked the sharp commencement whereas Wharton read the peak of the first great wave 1 hr 15 min later. We cannot agree

to Wharton's reading for the commencement at San Francisco (Figure 4) and have chosen instead the long waves beginning at 27-09-40. Similarly at Honolulu and St. Paul (Figures 3, 4) we disregard the minor disturbance read as the commencement by Wharton (for Honolulu this occurs at a time prior to the major explosion at Krakatoa) and agree with his time for the first great wave. The disturbances on the Williamstown and Portland records are small and any reading is open to some question.

Expected minus observed times for the air induced sea waves are listed in Table I. In nine cases the differences are less than one hour and in five cases the differences range from one to two hours. In one case, St. Paul, the difference is four and a half hours. It is significant that the tidal disturbances at the English Channel stations correlate with air wave II which arrives from the ocean side via the Antipodes rather than with the direct wave I which arrives from the land side. Excellent indications of waves I and II may be found on the Port Moltke marogram (Figure 3). These correlations may well be expected if the tidal disturbances were induced by the air wave. The discrepancy at St. Paul may be due to the fact that wave I is blocked by the Alaskan Peninsula and wave II is almost blocked by the North American mainland. The hypothesis of air coupling can well explain the origin of the tidal disturbances recorded at remote stations on Aug. 27-29, 1883,

and relates these disturbances to the Krakatoa explosion. It was the absence of a suitable mechanism of propagation that forced the earlier investigators to the conclusion that unrelated seismic movements caused the tidal disturbances.

It is this inescapable conclusion of coupling of barometric disturbances of the Krakatoa type to the ocean which led to the series of experimental and theoretical investigations (reported above) of different types of air coupled surface waves. In this later work it was established that the great density contrast between air and water, ice, or rock required equality of phase velocity in the two media before strong coupling could occur. The absence of a known free wave in the ocean with phase velocity equal to the speed of the Krakatoa air wave (1100 km/sec) suggests two possibilities: (1) significant coupling to the ocean can occur "off resonance" or (2) a free ocean surface wave with a speed close to 1100 km/sec exists. These possibilities are now being investigated.

<u>Table I</u>

Air and Sea Wave Arrival Times

	Air Wave Arr. Hours after 00 27 Aug. 1883		Air Wave Arrival Local Time		Wharton's time of sea wave travel in shallow water	Wharton's observed sea wave arrival Local Time		* Expected time of arrival for air induced sea wave Local Time		Our observed sea-wave arrival time Local Time		Expected minus observed air-sea wave	
	I	II	I	II		commencement	1st great wave	I	II	I	II	I	II
	h:m	h:m	d: h: m	d: h: m	Min.	d: h: m	d: h: m	d: h: m	d: h: m	d: h: m	d: h: m	h:m	h:m
Port Moltke (S. Georgia)	15:15	28:00	27:12:48	28:01:33	7	27:14:00	28:01:45	27:12:55	28:01:40	27:14:00	28:01:30	-01:05	+00:10
Orange Bay (Cape Horn)	16:00	27:00	27:11:28	27:22:28	63	27:14:20	27:21:57	27:12:31	27:23:31	27:14:00	27:21:50	-01:29	+01:41
Colon	20:30	22:00	27:15:10	27:16:40	25	- - - - -	27:16:30	27:15:35	27:17:05	27:15:15	?	+00:20	- - -
Socoa	14:00	27:45	27:13:53	28:03:38	30	- - - -	28:04:50	27:14:23X	28:04:08	X	28:04:50	X	-00:42
Rochefort	13:45	27:45	27:13:41	28:03:41	197	28:07:40	28:09:20	27:20:58X	28:06:58	X	28:07:30	X	-00:32
Devonport	14:00	27:45	27:13:43	28:03:28	184	28:06:20	28:10:45	27:16:47X	28:06:32	X	28:06:40	X	-00:08
Cherbourg	14:00	27:45	27:13:54	28:03:39	286	28:09:20	28:09:20	27:18:40X	28:08:25	X	28:09:20	X	-00:55
Portland	14:00	27:45	27:13:50	28:03:35	274	- - - -	28:10:15	27:18:24X	28:08:09	X	28:07:20?	X	+00:49?
Havre	14:00	27:45	27:14:00	28:03:45	410	28:11:33	28:11:33	27:20:50X	28:10:35	X	28:11:33	X	-00:58
Williamstown (Australia)	08:30	34:00	27:18:09	28:19:39	138	- - - -	28:04:40	27:20:27X	28:21:57	28:01:00 X→R_1	28:20:00?	X	+01:57?
Honolulu	14:00	28:45	27:03:29	27:18:14	11	26:14:00	27:03:20	27:03:40	27:18:25	27:03:20		+00:20	- - -
St. Paul's (Kodiak)	13:30	30:00	27:03:22	27:19:52	88	27:01:30	27:16:45	27:04:50X	27:21:20		27:16:45	X	+04:35
Saucelito (San Francisco)	16:00	27:00	27:07:50	27:18:50	43	27:00:00	27:13:10	27:08:33	27:19:33X	27:09:40	X	-01:07	X

I direct path
II path through Antipodes
* obtained by adding time of sea wave travel in shallow water to air wave arrival
X air-sea wave blocked by land
R_1 sea wave reflected from Antarctica?

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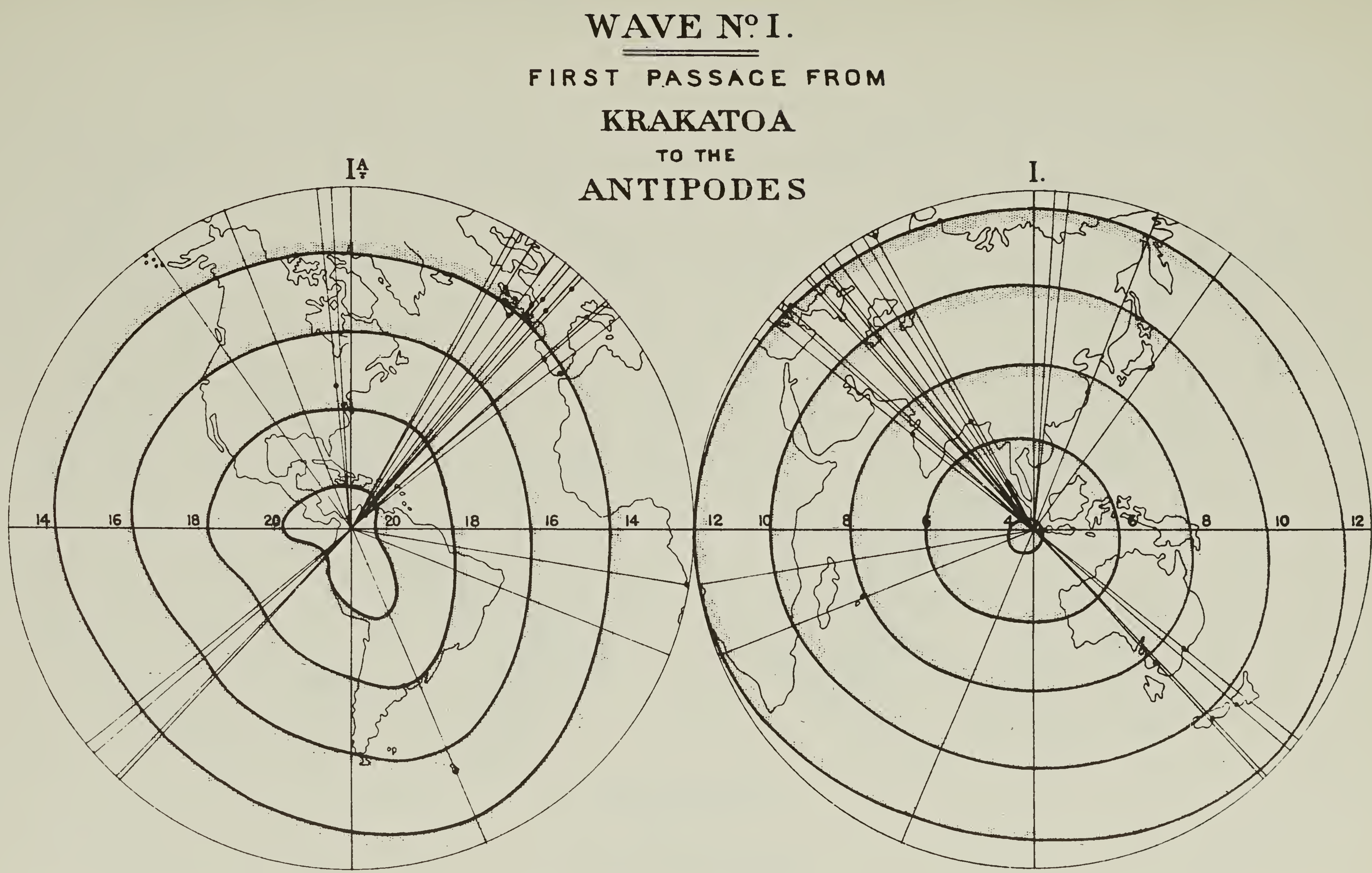

Figure 1. Travel times of aerial wave in first passage from Krakatoa. Time is in hours after 00 GCT, Aug. 27, 1883.

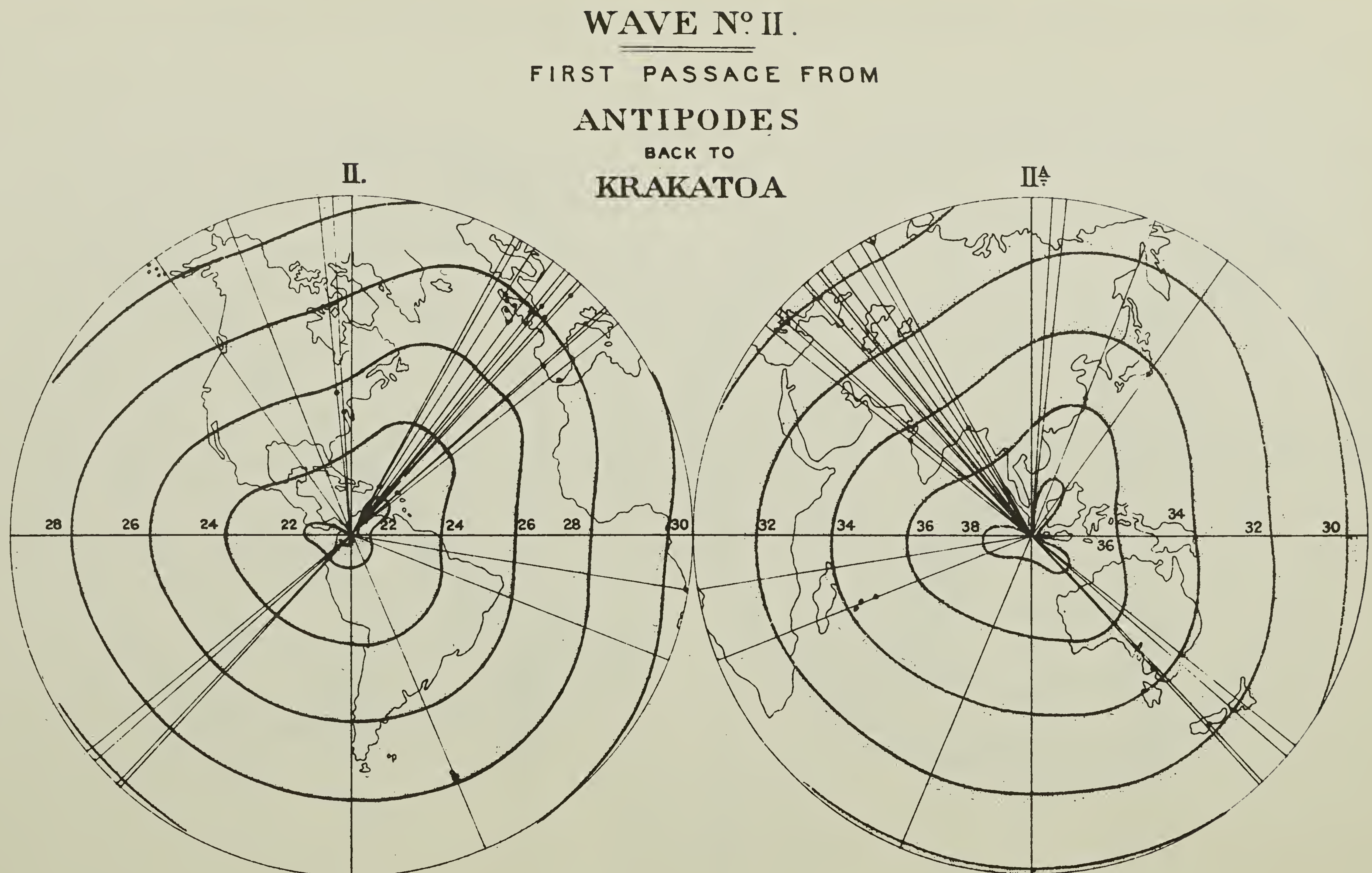

Figure 2. Travel times of aerial wave in first passage from Antipodes to Krakatoa. Time is in hours after 00 GCT Aug. 27, 1883.

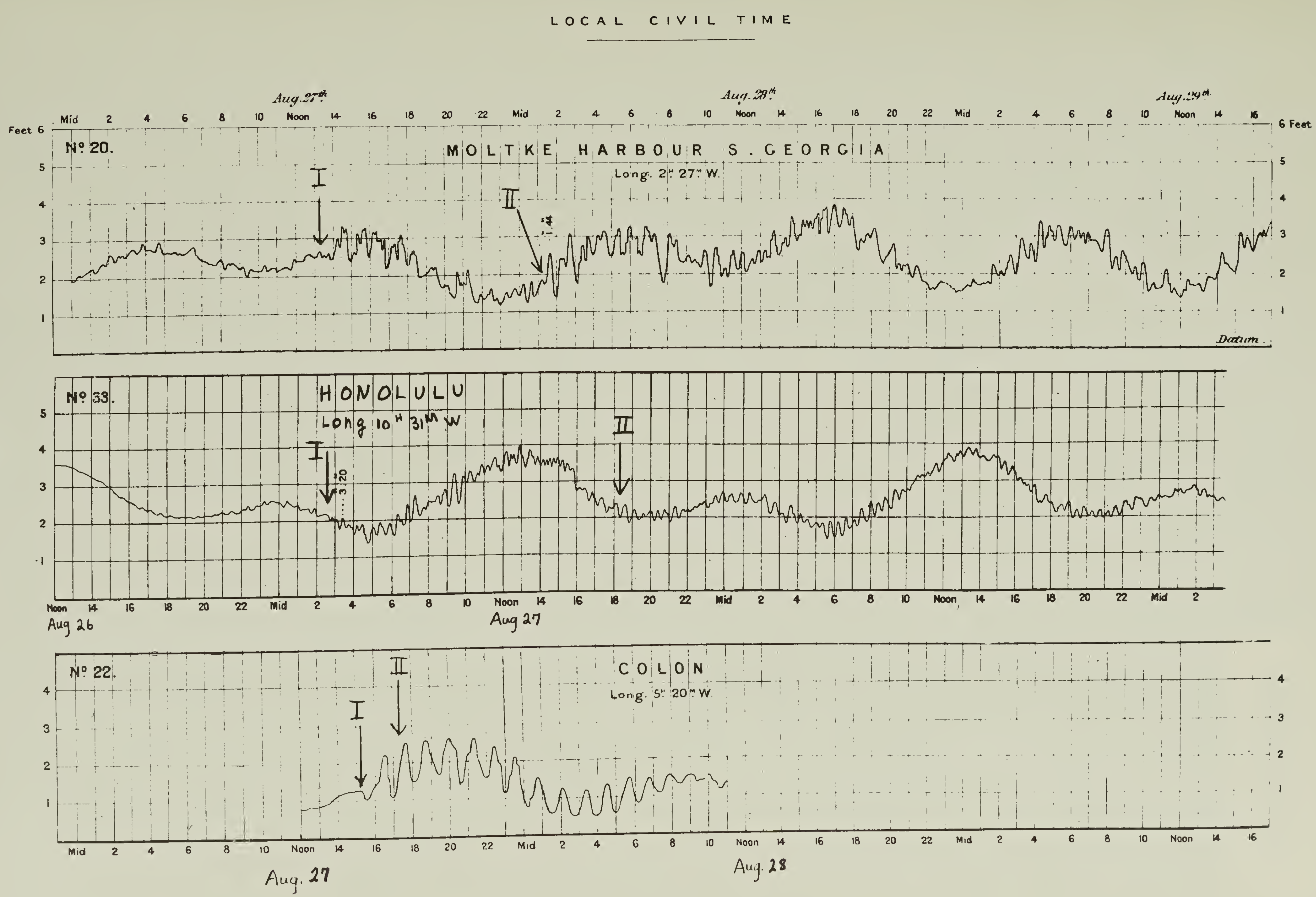

Figure 3. Marograms from S. Georgia, Honolulu and Colon for Aug. 27-29, 1883 (after Symons, 1888). Expected time for air-induced sea waves I and II is shown by arrows.

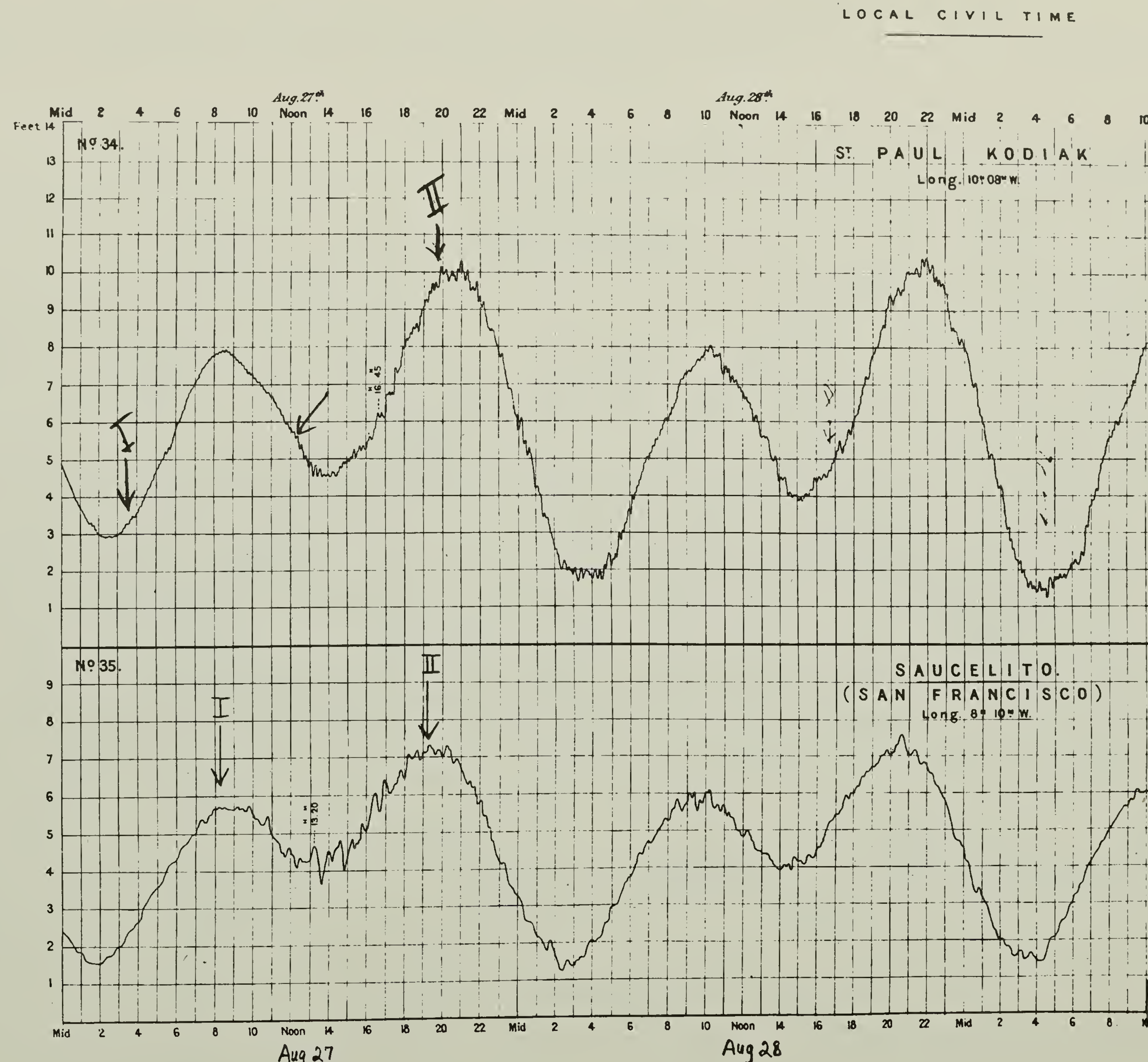

Figure 4. Marograms for Kodiak and San Francisco for Aug. 27-29, 1883 (after Symons, 1888). Expected time for air-induced sea waves I and II is shown by arrows.